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LCA FOR ENERGY SYSTEMS

Life cycle assessment of potential energy uses for short rotation willow biomass in Sweden

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Abstract
Purpose Two different bioenergy systems using willow chips as raw material has been assessed in detail applying life cycle assessment (LCA) methodology to compare its environmental profile with conventional alternatives based on fossil fuels and demonstrate the potential of this biomass as a lignocellulosic energy source.
Methods Short rotation forest willow plantations dedicated to biomass chips production for energy purposes and located in Southern Sweden were considered as the agricultural case study. The bioenergy systems under assessment were based on the production and use of willow-based ethanol in a flexi fuel vehicle blended with gasoline (85 % ethanol by volume) and the direct combustion of willow chips in an industrial furnace in order to produce heat for end users. The standard framework for LCA from the International Standards Organisation was followed in this study. The environmental profiles as well as the hot spots all through the life cycles were identified.
Results and discussion According to the results, Swedish willow biomass production is energetically efficient, and the destination of this biomass for energy purposes (independently the sort of energy) presents environmental benefits, specifically in terms of avoided greenhouse gases emissions and fossil fuels depletion. Several processes from the agricultural activities were identified as hot spots, and special considerations should be paid on them due to their contribution to the environmental impact categories under analysis. This was the case for the production and use of the nitrogen-based fertilizer, as well as the diesel used in agricultural machineries.
Conclusions Special attention should be paid on diffuse emissions from the ethanol production plant as well as on the control system of the combustion emissions from the boiler.

Keywords Biomass · Bioenergy · Ethanol · Gasoline · Heat production · LCA · Natural gas · *Salix spp*

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1 Introduction

Nowadays, there is a growing concern regarding climate change, atmospheric pollution, and depletion of fossil resources, which has led to an interest in the use of renewable fuels (Reijnders and Huijbregts 2007; Mizsey and Racz 2010). Currently, 40 % of the total energy consumption worldwide is in the form of liquid fuels such as gasoline and diesel (Tan et al. 2008, de Paula Gomes and Muylaert de Araújo 2009). In fact, transport is almost fully dependent on these kinds of liquid fuels. Liquid biofuels, especially ethanol, provide one of the few options for fossil fuels substitution in the short- to medium-term and are strongly promoted by the European Union (European Union 2003): They have the potential to offer both greenhouse gases (GHG)-saving and a secure supply of energy (Taylor 2008; Kim and Dale 2004). In fact, crop-derived fuels have been called climate neutral, as they release to the atmosphere carbon that was fixed by photosynthesis (Reijnders and Huijbregts 2007).

Ethanol derived from biomass has the potential of being an environmental friendly transportation fuel as well as an alternative to gasoline (Reijnders and Huijbregts 2007; Bai et al. 2010). It is used in the light duty vehicle fleet in a large number of countries (Reijnders and Huijbregts 2007; Zhi Fu et al. 2003). Usually, ethanol has been produced from starch and sugar crops such as sugar beet (Halleux et al. 2008), cassava (Nguyen and Gheewala 2008a), barley (Lechón et al. 2005), corn (Spatari et al. 2005), or sugarcane (Luo et al. 2009a). However, another variety of biomass feedstocks can be used for ethanol production (called second-generation ethanol) such as mill wastes, municipal solid wastes, and/or lignocellulosic biomass. These lignocellulosic resources are receiving special interest, driven by concerns over high fuel prices, security of energy supplies, global climate change, and the search of opportunities for rural economic development. However, their conversion technology could not be commercialized in 10 years or more (Mizsey and Racz 2010).

Biomass combustion is an important source of renewable energy not only in large heat and power plants but also in residential combustion systems. In fact, in some regions such as Scandinavia, locally produced biofuels are being used to fire small units for district heating (Lillieblad et al. 2004). Biomass is the most important fuel in Swedish district heat production representing the wood based fuels a remarkable ratio (Eriksson et al. 2007). However, the use of biomass for heat production has been quite controversial due to concerns with possible increase in health impact specifically when natural gas is changed in the boiler by biomass and the community is densely populated (Pa et al. 2011). Wood combustion can be an important emission source of air pollutants such as volatile organic compounds, polycyclic aromatic hydrocarbons (PAH), and particulate matter. Therefore, the promotion of the use of biomass in combustion systems must be accomplished by a development of new combustion technologies, which minimize these emissions (Pettersson et al. 2010).

Therefore, all these situations have motivated more and more support for the use of renewable energies. In this context, several energy scenarios and policy objectives indicate a growing increase in the production and use of biomass resources as an energy resource of electricity, heat, and liquid fuel generation (Eriksson et al. 2007; Heller et al. 2004; van Dam et al. 2009). Short-rotation forest (SRF) plantations have been regarded as an important alternative in the shift towards a more sustainable energy supply, to substitute fossil fuels in Europe (Havlík et al. 2011). It is the main driving force for the development of advanced process technologies to produce fuels from lignocellulosic materials. However, discussion persists concerning the competition with land use requirement for food and feed production (Havlík et al. 2011). In fact, in Sweden the land-use alternative to willow is agricultural crops, most commonly cereals (Dimitriou et al. 2012), but only low-quality lands are considered. Among the different plantations for energy uses, fast-growing hardwoods are receiving special attention, especially willow (*Salix spp.*), which is among the few planted commercially to a significant extent in the European Union (EU) (Mola-Yudego and Aronsson 2008; Mola-Yudego and González-Olabarria 2010).

There are currently no official accounts about the area of commercial willow plantations in the EU. The reports indicate that, in 2009, there were c. 14,000–16,000 ha planted in Sweden, c. 1,500 ha in Denmark, and 6,444 ha in UK (Mola-Yudego 2010; Statistics 2007; Defra 2009).

The present study is focused on willow biomass feedstock, a SRF crop which is cultivated for the production of wood chips commonly used for heat generation. Willow is a suitable crop for the climatological conditions of Northern and Western Europe, and it can be used as a raw material not only for energy production but also for, e.g., building materials, geotextiles, paper, and packaging materials (Venturi et al. 1999). Moreover, this crop is extensively cultivated in Sweden, being the leader in Europe in commercial plantations (Börjesson and Tufvesson 2011). Nowadays, there are around 14,000 ha of short-rotation willow plantations established. Willow has been cultivated as an agricultural crop for energy purposes in Sweden since the 1980s, and it is considered as an important crop for the production of wood fuel for the Swedish energy sector (Mola-Yudego and Aronsson 2008; Mola-Yudego 2010). In fact, Sweden provides an excellent example of successful use of energy crops, since many Swedish district heating facilities rely on a combination of forest residues and willow chips. The advantages of the agricultural production of willow include: (1) efficient land use in combination with the increasing demand for renewable energy sources, (2) the increment of biodiversity, positive effects on rural economies as a diversification of farm crops, (3) the additional possibilities for environmental control and wastewater treatments, (4) it fits well with current farm operations, and finally, (5) it demands low economic investments after the establishment is made (Mola-Yudego 2010).

Willow can be an ideal candidate for lignocellulosic ethanol production (Börjesson and Tufvesson 2011) and an alternative to other energy crops since its biomass presents a chemical composition richer in cellulose and hemicellulose which are the main raw materials for sugar conversion. In addition, willow could also be interesting in comparison with the use of forest waste for this purpose, since these wastes are commonly used as raw materials in power plants (heat and electricity production) (Heller et al. 2004; Hedegaard et al. 2008).

In order to assess the effects of the potential energetic uses of willow, life cycle assessment (LCA) has been

proposed for their evaluation. LCA has been used in recent years to evaluate a wide range of bioenergy systems and for comparison purposes with fossil fuels energy systems. Examples include lignocellulosic ethanol production (Bai et al. 2010; Spatari et al. 2005; Luo et al. 2009b; Nguyen and Gheewala 2008b); biomass district heat production (Eriksson et al. 2007; Pa et al. 2011), electricity production (Heller et al. 2004; Rafaschieri et al. 1999), as well as pellet production for energy uses (Pa et al. 2011).

The aim of this study is to analyze from an environmental point of view two potential uses of willow biomass, which were compared with conventional alternatives:

1. The production and use of willow biomass-based ethanol in a flexi fuel vehicle. In particular, the analysis compares the environmental performance of ethanol in an 85 % blend with gasoline (E85) with conventional gasoline (CG).
2. The combustion of willow chips in an industrial furnace (<100 kW), in order to produce heat for end users. In addition, this system is compared with the production of heat from natural gas. Natural gas was assumed as fossil fuel for comparison because it is available at the Swedish west coast where it is used for district heat production (Eriksson et al. 2007) and where willow plantations are located.

In both cases, the analysis includes the assessment in detail of the production of willow chips from a commercial SRF plantation located in western Sweden.

2 Methodology

LCA approach is defined as a methodology for the comprehensive assessment of the impact that a product has on the environment throughout its life cycle (from extraction of raw materials through manufacturing, logistics and use to scrapping and recycling, if any), which is known as a “from cradle to grave” analysis (ISO 14040 (2006).

2.1 Goal and scope definition

This study is mainly focused on commercial willow plantations for biomass growing in Sweden. Although the main assumptions are based on Swedish conditions, regarding growth and management, the study is not restricted to Sweden, and it can be applied to other countries. Moreover, it is important to remark that electricity requirements (when necessary) are taken from the Swedish national grid which affects the results. Potentially, willow biomass can be converted into a variety of energy forms and carriers. It can be combusted in a boiler to produce heat for industrial uses and for district heating or into electricity. Moreover, willow biomass can be converted into hydrogen and ethanol for their use as transport fuels. Therefore, the aims of this study were to evaluate the environmental impacts of two bioenergy systems from willow biomass and their comparison with conventional energy systems. Moreover, the hot spots all over the bioenergy systems life cycle were identified, and measures were suggested for environmental improvement. The potential energy alternatives proposed for assessment were:

Alternative A1	Production of lignocellulosic ethanol from willow chips and use in a formulation of 85 % ethanol (*v/v*) and 15 % gasoline (E85) in a FFV.
Alternative A2	Production and use of CG in a FFV.
Alternative B1	Production of heat for end users in an industrial boiler (<100 kW) with an efficiency of 80 % from willow chips.

The conventional alternatives to be compared with the new ones were:

Alternative B2	Production of heat for end users in an industrial boiler (<100 kW) with an efficiency of 96 % from natural gas.

2.2 Functional unit and alternatives

In this study, two functional units (FU) have been managed, taking into account the different alternatives formulated. Concerning the alternatives A1 and A2, the function of the study is to drive a FFV (well-to-wheel analysis), so the FU chosen for comparison was 1 km distance-driven. Under these conditions, the amount of fuel required for travelling 1 km was calculated to be 66 g for CG and 92 g for E85. The average fuel economy considered in the FFV under study running with CG and E85 were 10.91 and 8.29 km/L, respectively (Kim and Dale 2006; Kreith and Goswami 2007).

Concerning the alternatives B1 and B2, the function of the study is to produce heat for different uses. Therefore, the FU assumed was 1 MJ of heat released from the combustion of willow chips and natural gas, respectively. In both cases, combustion heat was based on low heating value, and it was assumed the average net efficiency for the type of boiler available in the market (Dones et al. 2007). Heat distribution was not included in the analysis.

2.3 System boundaries (A1, A2, B1, and B2)

Figure 1 shows all the relevant processes involved in each alternative under assessment. The analysed bioenergy systems (A1 and B1) include the willow chips production subsystem, which is described in detail below. A representation of the forest activities involved in that subsystem are also shown in Fig. 1. Apart from all the field work, the production processes of the different forest inputs were also included, such as: diesel, herbicides, fertilizers, plants,

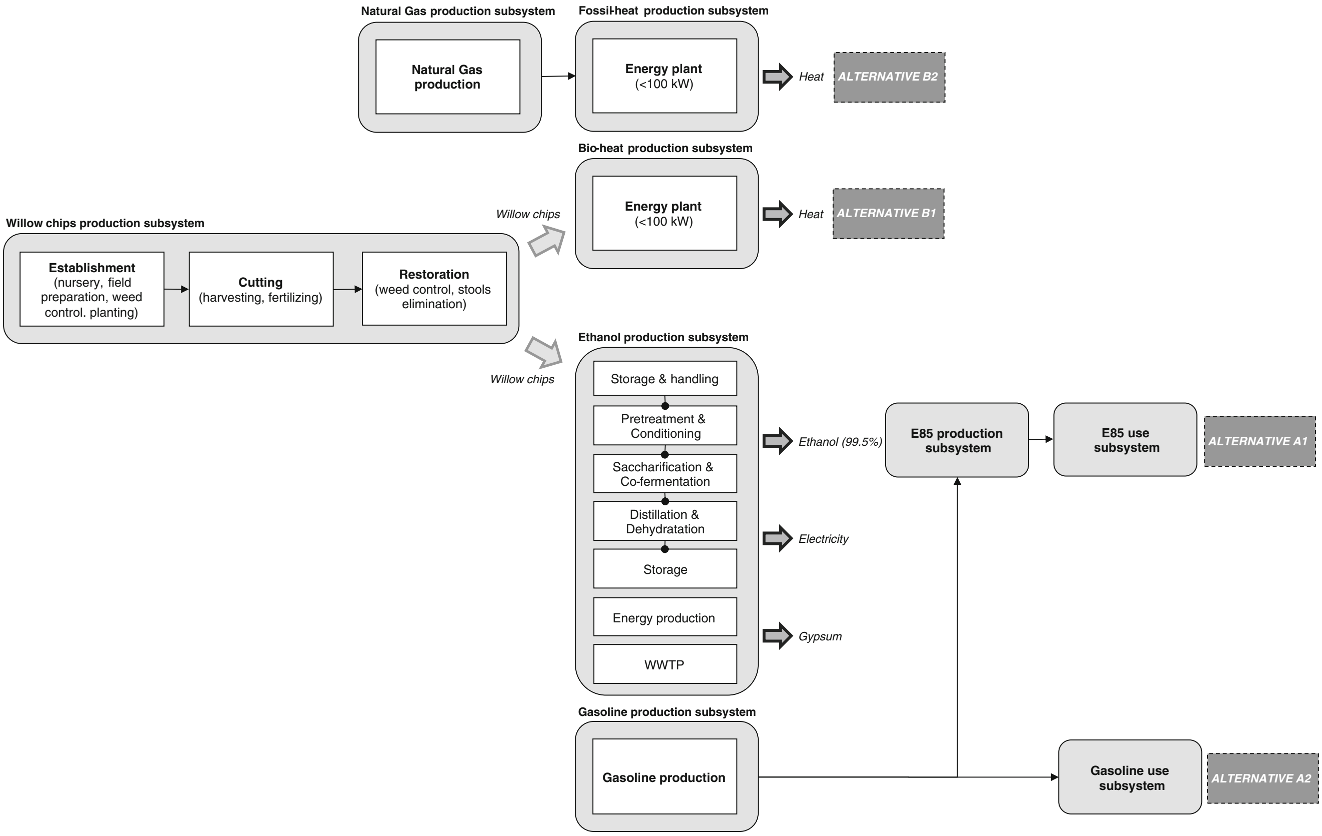

Fig. 1 System boundaries of the different alternatives under assessment

tractors, and forest utensils. The subsystems included in each alternative are the following:

Alternative A1 Willow chips production, ethanol production, E85 production, and E85 use subsystems.
Alternative A2 Gasoline production and gasoline use subsystems.
Alternative B1 Willow chip production and bio-heat production subsystems.
Alternative B2 Natural gas production and fossil-heat production subsystems.

- Willow chips production subsystem

This subsystem is common to both alternatives A1 and B1, where lignocellulosic biomass is processed to obtain two different types of bioenergy: ethanol and heat. A standard commercial hectare of willow cultivated in Southern Sweden was considered in this study. The willow plantation starts with land preparation related activities the year before planting with glyphosate in order to eradicate perennial weeds and couch grass. Moreover, the field must be ploughed during the autumn and harrowed to a depth of 6–10 cm. The planting step takes place in the spring and early summer, and it is established at ~10,000 plants/ha in twin row formations. After planting, weeds must be chemically controlled since they compete with nutrients and water. In the winter after planting, the year's shoots are cut back in order to let the plants develop a denser growth. Once the willow plantation is established, fertilization with nitrogen is required (either commercial fertilizer or sludge from wastewater treatment plants). Harvesting takes place in the winter when leaves have fallen and growth has finished. Commonly, the crop is harvested every 3–4 years, and the wood biomass reaches around 30–40 oven-dried[1] tonnes/ha in optimal growing conditions. Harvesting is carried out by means of a harvester that both cuts the rods and processes them into wood chips. New shoots grow from the coppice stools after harvesting, which means that there is no need for re-planting. Finally, the stools form new shoots during the spring and the plantation is sprayed with a mix of herbicides to kill off the willow plants.

- Ethanol production plant subsystem

In the ethanol conversion plant, willow chips are converted into ethanol by biological conversion. The ethanol production material and energy balances are based on the ethanol conversion technology reported by the U.S.

[1] Oven dried basis: the attainment of constant mass generally after drying in an oven set at 103±2 °C for 24 h.

National Renewable Energy Laboratory (Aden et al. 2002). The ethanol production process was simulated taking into account the willow biomass composition (Table 1). The conversion of the biomass involves enzyme-catalyzed hydrolysis, followed by fermentation and distillation steps. The model considered in this study assumes that most of the cellulose and hemicellulose carbohydrates in the feedstock are converted into soluble sugars and transformed into ethanol. This assumption is based on a current published study where ethanol production from corn stover was simulated (Humbird et al. 2011). Wastewater treatment (WWTP) is included in the assessment and biogas is produced from the distillation and evaporation condensates. Moreover, the lignin fraction present in the willow biomass together with other solids and the biogas are used as fuel to meet the energy requirements of the plant (electricity and steam). A surplus of electricity is produced in this subsystem which can be sent to external uses. Moreover, gypsum is produced in the pretreatment process after a filtered step from the hydrolysate stream. This gypsum presents 20 % of liquid but can be handled as a dry solid. This co-product can be used for different applications, such as fertilizer and soil conditioner or plaster ingredient. The production of the enzymes consumed in the conversion process was included within the subsystem boundaries. Transports of all consumable materials up to the plant gate were also included in this subsystem.

- E85 production subsystem

The distribution of ethanol from an ethanol conversion plant to a gasoline station was assumed to be done by 32-tonne diesel lorries. The average distance was assumed to be 160.8 km (Joyce 2010). The production of the gasoline as well as its transportation up to the gasoline station, the mixture of gasoline and ethanol to produce E85, and their regional storage were also included within the subsystem boundaries.

- E85 final use subsystem

Combustion of E85 in a representative FFV was evaluated and emissions were calculated according to the economy fuels and the functional unit selected (Kim and Dale 2006; Kreith and Goswami 2007; Kelly et al. 1996; Reading et al. 2002). Manufacture, maintenance, and disposal of the FFV were also included within the subsystem boundaries.

- Bio-heat production subsystem

This subsystem describes the combustion of willow chips in a furnace with an energy capacity of less than 100 kW, taking into account moisture content of the chips of 40 % and a low heating value around 4208 MJ/m^3 (Dones et al. 2007). The net efficiency assumed in this furnace to convert combustion heat to heat for end users was 80 %. Combustion emissions to air, the transport of willow chips from forest to the energy plant, the electricity production needed for operation, furnace installation, and disposal of ashes were included in the subsystem boundaries.

- Natural gas production and fossil-heat production subsystems

The natural gas production module includes the gas field exploration, the gas production, the purification, as well as the fuel distribution network in Sweden (Dones et al. 2007). Network losses assumed in this subsystem were based on assumptions. For all of these stages, air- and waterborne emissions, as well as energy and working material requirements and waste production were considered. The combustion of this fuel in a boiler with an energy capacity of less than 100 kW was considered assuming a net efficiency of 96 % (Reading et al. 2002). Combustion emissions to air, the electricity needed for operation and boiler infrastructure were included in the assessment.

- Gasoline production and gasoline use subsystems

Production and regional distribution of gasoline from the refinery to the gasoline station were taken into account in the gasoline production subsystem (Dones et al. 2007). Electricity needed and upstream related emissions were also included. Combustion emissions in a FFV were included in the use subsystem. Manufacture, maintenance, and disposal of the FFV were also included within the subsystem boundaries.

Table 1 Assumed composition (dry basis) of feedstock delivered to the ethanol plant gate (adapted from Jørgensen et al. 2007)

Component	Weight fraction
Cellulose	0.450
Hemicellulose	0.200
Lignin	0.250
Acetate	0.015
Ash	0.017
Others	0.069
Total	1.00

2.4 Inventory analysis

Inventory data collection in order to build the Life Cycle Inventory (LCI) is the most effort-consuming step of the execution of LCA studies. Data used in this study were collected from different sources and in many different ways: field data, research reports, and literature. Background information from willow cultivation was obtained from field data of Swedish plantations dedicated to this energy crop production (González-García et al. 2012a). Table 2 gives a timeline for the major operations undertaken in willow management.

Table 2 Willow chip-related field operations timeline (between parenthesis: number of repetitions)

Year	Activity short rotation willow plantation
−1	Weed control, ploughing, and harrowing
0	Planting and weed control
1	Cut back
2–4	Fertilizing (2) and harvesting
5–7	Fertilizing (2) and harvesting
8–10	Fertilizing (2) and harvesting
11–13	Fertilizing (2) and harvesting
14–16	Fertilizing (2) and harvesting
17–19	Fertilizing (2) and harvesting
20	Weed control, stools extraction, and stools collection

The production of the different consumable inputs such as the fertilizer (calcium nitrate), the pesticides (glyphosate and gardoprim), and the used machinery were taken from Ecoinvent database (Althaus et al. 2007). Diffuse emissions from fertilizer application and emissions from agricultural machinery (fertilizing, planting, harvesting, and transport) have also been taken into account (González-García et al. 2012a). Field information concerning labour hours, diesel consumption, and agrochemicals doses were directly supplied by the growers and taken from González-García et al. (2012a).

The binding of CO_2 from the atmosphere was also taken into account and estimated by the C-content in the dry matter multiplied by the stoichiometric factor 44/12, based on the assumption that the carbon in the biomass is completely taken from the air (~1.81 kg CO_2/kg dried biomass).

The conversion process of lignocellulosic ethanol was modelled following the conversion technology developed by the U.S. National Renewable Energy Laboratory (Aden et al. 2002; Humbird et al. 2011) but adapted to willow composition with a biomass capacity treatment of ~96 ton/h. This technology based on a simultaneous saccharification and fermentation technology was chosen due to the precision on the inventory data presentation. Table 3 shows the specific LCI data for the ethanol production subsystem (mass and energy balances). Combustion emissions from E85 use in a FFV were taken from Kelly et al. (1996) and Reading et al. (2002).

Concerning heat production from willow chips, combustion emissions, infrastructure, wood chips requirement, net efficiency of boiler, and electricity consumption were taken from the Ecoinvent database (Dones et al. 2007), but assuming willow as a raw material. Information for the conventional alternative B2 was also taken from the Ecoinvent database (Dones et al. 2007). Concerning the alternative A2, inventory data for the gasoline production were taken from the Ecoinvent database (Dones et al. 2007) and combustion emissions from Kelly et al. (1996) and Reading et al. (2002).

Table 3 Global LCI data for the ethanol production plant subsystem

Inputs from the technosphere			
Materials	Value	Energy	Value
Willow biomass (25 % moisture)	95.96 tonnes	Electricity[a]	25,228 kWh
Vinyl acetate	27.4 kg	Steam[a]	1,414,200 MJ
Sulfuric acid	2540 kg		
Lime	1,852 kg	Transport	Value
Diammonium phosphate	24 kg	Lorry (16 ton)	2,981.8 tkm
Corn steep liquor	188 kg		
Enzyme	7,111 kg		
Nutrient feed	48 kg		
Inputs from the environment			
Materials	Value		
Well water	161.4 m^3		
Outputs to the technosphere		Outputs to the environment	
Product and co-products	Value	Emissions to air	Value
Ethanol (99.5 %)	21,377 kg	Vapor	201.9 ton
Gypsum	4,274 kg	Carbon dioxide	88.3 ton
Electricity	10,410 kWh	Acetic acid	116.6 kg
		Ethanol	16.4 kg
Wastes to treatment	Value	Sulfuric acid	2.0 kg
Ash (to landfill)	1682 kg	Others	247.4 kg
Others (to landfill)	1446 kg		

[a] From energy production process from solid wastes and biogas

2.5 Allocation procedure

Allocation is one of the most critical issues in LCA. It is required for multi-output processes and the selection of an allocation approach for processes that produce more than one co-product can have a strong effect on the results. In this study, an allocation procedure was required since different value products are co-produced in the ethanol production subsystem: ethanol, electricity, and gypsum. Therefore, the economic value of the different co-products was used as the basis for allocation (economic allocation) due to the large differences on the market prices between the co-products and ethanol is the driving force of this production process. Table 4 shows a short description of the allocation factors considered in this case study.

Willow chips production related activities involve the production of not only willow chips but also forest biomass residues/waste. In this study, the environmental loads derived from this subsystem were totally allocated to the willow chips, since the chips are the driving force of this type of commercial plantations and forest waste remains on the soil.

3 Life cycle energy and environmental performance

Among the phases defined by the impact assessment phase in the LCA methodology (ISO 14040 2006), only classification and characterization stages were considered. Normalization and evaluation were excluded, since they are optional elements and according to the goal and scope defined here they would not provide extra useful information. Characterization factors reported by the Centre of Environmental Science of Leiden University (CML 2 baseline 2000 method) were considered (Guinée et al. 2002), and the potential impact categories analyzed are: abiotic resources depletion (AD), acidification (AC) and eutrophication (EP), global warming (GWP), ozone layer depletion (OLD), human toxicity (HT), fresh water aquatic ecotoxicity (FE), marine aquatic ecotoxicity (ME), terrestrial ecotoxicity (TE), and photochemical oxidants formation (PO).

Table 4 Partitioning fraction for economic allocation

Product	Production	Price	Allocation factor
Ethanol	21,377 kg	0.805 €/kg[a]	91.2 %
Gypsum	4,274 kg	0.0146 €/kg[b]	0.3 %
Electricity	10,410 kWh	0.1536 €/kWh[c]	8.5 %

[a] Börjesson and Tufvesson 2011

[b] Aden et al. 2002

[c] www.energy.eu/#domestic [value for Sweden; accessed June, 2011]

3.1 Comparison between E85 and CG production and use in a FFV (A1 and A2)

Alternatives A1 and A2 are based on the production and use of a fuel (E85 and CG, respectively) in a FFV. Table 5 summarizes the LCA characterization results (per kilometer) for both scenarios. According to these results, a reduction in the environmental loads was possible in several impact categories when CG is substituted by E85, except in AP, EP, HT, FE, TE, and PO where the effect from forest activities is considerably high. An important improvement has been achieved in GWP when E85 is used as transport fuel with a reduction of 64 % of GHG emission per kilometer.

Figure 2 shows the contributions to each impact category for the subsystems involved in A1. According to this figure, the main contributor to almost all the categories was the willow chips production subsystem, which involves the forest activities related to the production of the willow biomass.

Concerning the AD contributors, E85 production is the main hot spot followed by willow chips production with contributions of 49 % and 38 %, respectively, due to the gasoline (15 % gasoline by volume in the blend) and diesel used in the forest activities.

Nitrogen oxides from the E85 use subsystem, the diesel combustion in forest machineries (specifically in the harvester), and the diffuse emissions from N-based fertilizer application represent 43 % of total acidifying emissions. The emission of sulphur dioxide (39 %) derived from diesel combustion in harvesters and agrochemicals production (calcium nitrate) is also outstanding.

Diffuse emissions from nitrogen-based fertilizer application was the main hot spot in EP (83 %) mainly due to nitrate leaching (79 % of total eutrophying emissions) followed by nitrogen oxides (9 %), derived from E85 use in the FFV and from the diesel combustion in tractors.

With regard to GWP, it is important to remark the positive effect of the CO_2 sequestered by the biomass which helps to counteract the 64 % of the GHG emissions derived all over the life cycle (see Fig. 2). Ethanol production related activities considerably influence the results due to electricity and heat production in the cogeneration boilers from the lignin fraction, solids waste, and biogas from the WWTP. This ethanol plant is energy self-sufficient and produces a surplus of electricity which can be sold to nearby industries or neighborhoods. The production of enzyme (on site) is also interesting in terms of GHG emissions together with the inputs delivery.

In terms of OLD, the main hot spot was the E85 production subsystem due to gasoline requirement production (50 % of total). The second most important contributor

Table 5 Environmental impacts estimated per functional unit (1 km) for scenarios A1 and A2

Category	Unit	A1	A2	Change[a]
Abiotic depletion (AD)	g Sb eq	0.731	1.67	−56.2 %
Acidification (AC)	g SO_2 eq	0.806	0.734	+10.2 %
Eutrophication (EP)	g PO_4^{-3} eq	0.963	0.097	+891 %
Global warming (GWP)	kg CO_2 eq	0.092	0.257	−64.1 %
Ozone layer depletion (OLD)	mg CFC-11 eq	0.013	0.031	−58 %
Human toxicity (HT)	g 1,4-DB eq	33.67	28.13	+19.7 %
Fresh water aquatic ecotoxicity (FE)	g 1,4-DB eq	3.67	2.90	+26.5 %
Marine aquatic ecotoxicity (ME)	kg 1,4-DB eq	10.71	19.16	−44.1 %
Terrestrial ecotoxicity (TE)	g 1,4-DB eq	0.241	0.190	+26.5 %
Photochemical oxidants formation (PO)	g C_2H_4 eq	0.153	0.072	+112 %

A1: E85; *A2*: CG

[a]% Change of relative to A2

was the willow chips production related subsystem (34 %), mainly due to the diesel consumption in forest activities (such as in the harvester). Contributing substances to this impact category were Halon 1,301 (84 %) and Halon 1,211 (14 %), derived from these fuels production.

Concerning the toxicity-related impact categories (HT, FE, ME, and TE), once again the main hot spot was the subsystem related with the production of the willow biomass (see Fig. 2). Diesel combustion in forest machineries due to PAH emission to the air (26 % of total contributing substances) was the most important contributor to HT. Nickel ion emissions to water (mainly those derived from the infrastructure of N-based fertilizer and machinery production processes) were responsible for 38 % of total contributing emissions followed by vanadium emissions (23 %). Concerning ME, emissions related with the infrastructure considerably influence the results. Therefore, the contribution of barite emissions to water and vanadium emission to air were 37 % and 18 %, respectively, of total contributing substances. Finally, concerning TE, vanadium (44 %) and mercury (19 %) to the air derived from infrastructure were the main responsible for contributions to this impact category.

With regard to PO, the use of E85 as fuel in a FFV contributes to 40 % of total photochemical oxidants emissions due to acetaldehyde and carbon monoxide emissions (21 % and 18 % of total, respectively). Ethanol production related activities are also a hot spot with contributions of 51 % mainly attributable to biomass pre-treatment stage due to acetic acid emissions.

3.2 Comparison between willow chip-based heat and natural gas-based heat production (B1 and B2)

Alternatives B1 and B2 are based on the production of heat in an industrial boiler (<100 kWh) using willow chips and natural gas as fuel, respectively. Table 6 summarizes the LCA characterization results (per MJ) for both scenarios. According to the comparative results, substituting natural gas for willow chips as fuel in an industrial boiler seems to present environmental improvements in terms of several impact categories: AD, GWP, OLD, and ME. On the

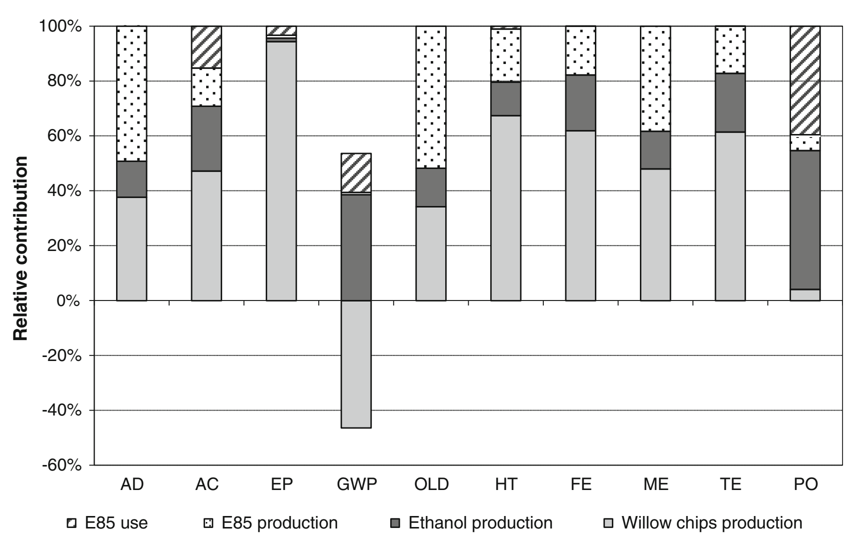

Fig. 2 Contributions of key subsystems to the impact categories under assessment when E85 is used as transport fuel in a FFV (alternative A1)

Table 6 Environmental impacts estimated per functional unit (1 MJ) for scenarios B1 and B2

Category	Unit	B1	B2	Change[a]
Abiotic depletion (AD)	g Sb eq	0.057	0.512	−88.9 %
Acidification (AC)	g SO_2 eq	0.160	0.020	+709 %
Eutrophication (EP)	g PO_4^{-3} eq	0.184	0.004	+4215 %
Global warming (GWP)	g CO_2 eq	35.22	63.35	−44.4 %
Ozone layer depletion (OLD)	mg CFC-11 eq	0.001	0.005	−80.4 %
Human toxicity (HT)	g 1.4-DB eq	17.37	12.70	+36.8 %
Fresh water aquatic ecotoxicity (FE)	g 1.4-DB eq	0.974	0.309	+215 %
Marine aquatic ecotoxicity (ME)	kg 1.4-DB eq	1.42	6.34	−77.6 %
Terrestrial ecotoxicity (TE)	g 1.4-DB eq	0.145	0.038	+278 %
Photochemical oxidants formation (PO)	g C_2H_4 eq	0.006	0.003	+150 %

B1 bio-heat, *B2* fossil-heat

[a]% Change of relative to B2

contrary, natural gas is the best option in the remaining categories.

Figure 3 shows the distribution of contributing processes to each impact category under assessment for scenario B1. According to the results, willow chip production (which includes all forest activities dedicated to biomass production) is the main hot spot in AD, EP, OLD, FE, and ME. In terms of GWP, this subsystem is also responsible for the CO_2 sequestration during the biomass growth which counteracts part of the derived GHG emissions (97.1 g CO_2 MJ^{-1}). Combustion emissions from the biomass combustion in the boiler are the main hot spot in AC, HT, and PO, as well as are the main responsible for GHG emission in the GWP. Concerning TE, the electricity production required in the combustion process, which is taken from the Swedish national grid, together with the wood ash disposal in a land farming and municipal incinerator, are the main contributors. The contributions to all impact categories will be described in detail below.

Concerning AD, forest activities related with the willow chips production contributes to 80 % of total mainly due to diesel consumption in the harvesting step (17 %) as well as natural gas consumption in the calcium nitrate production process (48 %). The manufacture of the furnace is the second most important contributor (10 %) due to the requirement of hard coal.

In terms of AC, combustion emissions from the boiler are the main responsible for acidifying emissions with a contribution of 55 %, followed by wood chips production-related activities (39 % of total) due to the combustion emissions from diesel in the harvesting step (7 %), calcium nitrate production (7 %), and diffuse emissions from fertilizer application (26 %), mainly nitrogen oxides and ammonia. Concerning global contributing substances, nitrogen oxides are responsible for 73 %, followed by far for ammonia (11 %).

EP is an impact category that normally sees its characterization values increase when fossil fuels are substituted by a biomass source (Gasol et al. 2007) due to the diffuse emissions from the application of fertilizers to the forest field (mainly nitrate and nitrogen oxides). In this case study, agricultural activities are responsible for 82 % of eutrophying emissions due to nitrate and nitrogen oxides from calcium nitrate application. It is important to remark that diffuse emissions depend on several factors, such as the fertilizer

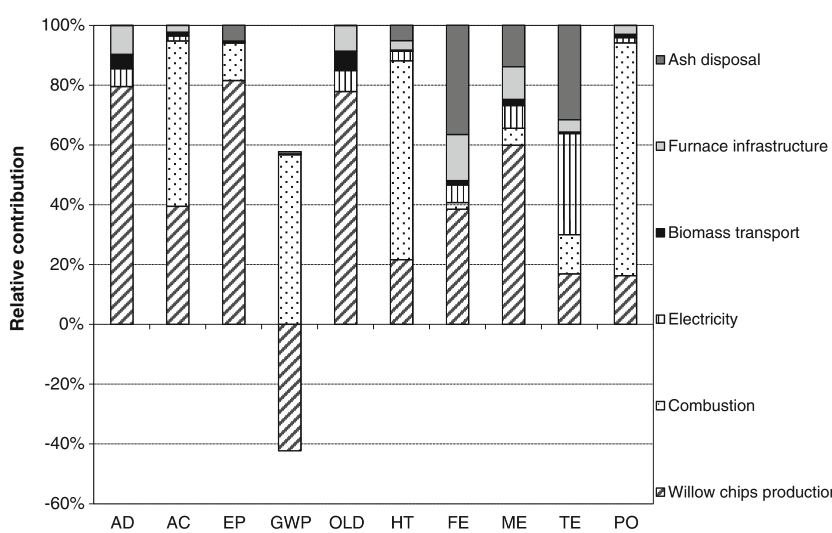

Fig. 3 Contributions of key processes to the impact categories under assessment when heat is produced from willow chips (alternative B1)

type, soil condition and/or drainage, weather, and timing of fertilizer application (Keoleian and Volk 2005).

With regard to GWP, the CO_2 fixed in growing the biomass crop balances the 73 % of fossil CO_2eq emissions which take place throughout the life cycle in forest machineries operation, agrochemicals production, infrastructure production, and transport activities. The most important hot spot of GHG emissions are the combustion emissions from the boiler, mostly CO_2.

OLD is considerably affected by the willow chip production process (78 % of total) due to Halon 1301 emissions from the production of diesel used in the harvesting step and production of natural gas used in the N-based fertilizer production.

Combustion emissions from the boiler are the main hot spot in the HT with a contribution of 68 % related to PAH (55 %) and benzene emissions (13 %). The second most important process is the willow chips production process which is responsible for 22 % of HT, due to PAH emission from diesel combustion in agricultural machineries.

Disposal of wood ash from the boiler in a landfarming and municipal incinerator and agricultural activities are responsible for 37 % and 39 %, respectively, of total impacts to FE, due to nickel and vanadium emissions to the water.

The willow chips production process generates 60 % of the environmental burdens linked to ME, mainly due to the fertilizer production (45 % of total). Emissions of vanadium to the air and barite and nickel to the water represent the 48 % of total contributing substances.

In the TE, the production of electricity required in the industrial boiler contributes to 34 % followed by the disposal of ashes (32 %) and willow chips production (17 %). Chromium and vanadium emissions to the soil represent 34 % and 12 % of contributing substances. These substances mainly derive from infrastructure and energy production.

Finally, combustion emissions from the boiler are the main hot spot in PO with a remarkable contribution of 78 % of total impacts, followed by the willow chip production process (16 %). Biogenic carbon monoxide emissions derived from the boiler (63 %) are the most important photochemical oxidant emissions, followed by sulphur dioxide (12 %). There is also fossil carbon monoxide derived from diesel combustion in agricultural machinery whose contributions add up to 5 %.

4 Discussion

Willow biomass can be converted in different types of energy forms and carriers in the same way as other feedstocks (Börjesson and Tufvesson 2011): ethanol, Fischer–Tropsch diesel, methanol, biogas, district heating, electricity, etc. The production of electricity by means of the co-firing of the willow biomass with coal has been analyzed by Heller et al. (2004), since willow energy crops are being promoted in the USA as a fuel source for increasing biomass energy and bioproduct demands. Reductions in GHG as well as SO_2 emissions up to 10 % when the co-firing rate of biomass is 10 % could be achieved (Börjesson and Tufvesson 2011). However, this environmental improvement considerably depends on the biomass composition, boiler configuration, and operating conditions.

Nowadays, practical foresters and theoretical scientists all over the world are looking for more energy-effective tree species under sustainable and efficient cultivation methods. This is the case of willow and also poplar, whose wood can be used for energy, paper, and construction wood (Christersson 2010). Poplar biomass (lignocellulosic feedstock) has been studied in detail as raw material for energy production in recent years. Rafaschieri et al. (1999) analyzed from the LCA perspective the production of electricity by means of a gasification process. According to this study, the biogas produced in the gasifier is used as fuel in a gas/steam combined cycle power plant. The production of electricity from biomass was compared with fossil-fuel-based electricity and environmental improvements were identified in terms of GWP (reduction ratio of 8.5 to 1). In fact, improvement actions were proposed specifically focused on the poplar biomass production process. González-García et al. (2010c) analyzed from an LCA point of view the production of ethanol from poplar biomass as well as it use in a FFV. According to this study, shifting from CG to ethanol-based blends presents a better environmental profile in terms of reduction of GHG emissions, as well as the avoidance of both abiotic and ozone layer depletion. Furthermore, reductions of fossil fuels extraction of up to 80 % could be achieved when pure ethanol (E100) is used as transport fuel. However, it is important to bear in mind that the use of ethanol blends increases the acidifying, eutrophying, and photochemical oxidant emissions.

Once again, the forest activities were identified as a hot spot all over the life cycle. Gasol et al. (2009) also considered the poplar biomass as raw material for a thermoelectric plant. Poplar was compared with Ethiopian mustard and natural gas as alternative fuels. The results of that study showed that the poplar bioenergy system is more energetically efficient in comparison with the others fuels. The replacement of natural gas combustion for district heating by wood waste and wood pellets gasification has also been analyzed in the literature (Pa et al. 2011).

According to our study, none of the bioenergy systems has absolute advantages over the others in all impact categories. However, important benefits can be achieved in terms of GWP. The use of a biomass source (in this case, willow chips) to produce heat can avoid at least 0.10 kg CO_2eq per kWh. If this biomass is used to produce E85 and taking into account the consequent use in a FFV, 0.17 kg

CO_2 eq per km can be avoided in comparison with the use of CG. Therefore, the selection will depend on the priorities of the decision makers.

As can be seen, there are numerous available studies that focus on the use of wood-based sources to produce different types of energy. In this particular study, we have considered the production of ethanol and its use in a FFV or for heating, as well as their comparison with conventional fossil fuels (gasoline and natural gas, respectively) using willow chips biomass as potential lignocellulosic feedstock in Sweden. In reference to the environmental results for both bioenergy systems considered, the highest environmental impacts are mainly associated with the willow chips production, mainly because of the use of N-based fertilizers and diesel use in agricultural machinery. Diffuse emissions from fertilizer application and fertilizer production are the main responsibilities for AC and EP environmental burdens in both energy systems. These results fit in with related studies such as Gasol et al. (2007, 2009) and González-García et al. (2009, 2010a, 2010b, 2010c), where lignocellulosic feedstocks are used as renewable source for energy purposes.

The parameters used in the calculations referred to willow cultivation were mostly based on general recommendations and intensive management, resulting in high yields. Although nowadays there are few commercial plantations reaching the yield levels considered, mostly concentrated in the south of Sweden (Mola-Yudego 2010), there is a trend of yield improvements along time that suggest that 10 oven-dry tonnes ha^{-1} $year^{-1}$ will be common in the future (Mola-Yudego 2011). There are, however, alternative management regimes that minimize the use of fertilizers, at the expense of lower yields (Mola-Yudego and Aronsson 2008), or consider the use of the plantations for phytoremediation (Dimitriou and Aronsson 2011). These alternatives can significantly reduce the impacts of AC and EP, although their discussion is out of the scope of this article, and can be the focus of future research. Finally, the methodology used did not have into account the overall changes in the soil conditions when compared with conventional agricultural uses. Recent studies have suggested positive effects of willow cultivation in the concentration of organic carbon, total nitrogen, and lower concentration of cadmium, among others (Dimitriou et al. 2012), and future studies can integrate these values for further evaluations.

However, the production (and use if the case) of biomass-based fuels presents greatest impact not only in AC and EP but also in PO and toxicity-related categories (HT, FE, and TE) due to combustion emissions. In other categories such as AD, OLD, and ME the bioenergy systems have less impact due to the lowest fossil fuels requirement all over the cycle. On the other hand, the CO_2 absorption credit taken into account for the growth of the willow biomass positively contributes to reducing the GHG emissions produced all over the life cycles (see Figs. 2 and 3) showing a remarkable environmental profile in terms of GWP in comparison with the conventional energy systems (see Tables 5 and 6).

Another aspect to remark on in this study is the production of electricity and gypsum together with ethanol in the ethanol production plant from willow chips. The production of both added-value co-products has been taken into account in this study considering economic allocation for distribution of the environmental burdens between the products. However, other authors (Börjesson and Tufvesson 2011) have considered the production of dried lignin in the ethanol production from lignocellulose, which can be used as fuel pellets, replacing wood pellets. In that study, economic and energy allocation were assumed. Although economic allocation varies over time due to variations in market prices of the products, it has seen that variations on prices of biofuels (specifically ethanol) are often smaller than the changes in prices indicate (Börjesson and Tufvesson 2011). Therefore, economic allocation could be a good allocation method.

Finally and according to the comparative results, environmental benefits can be achieved if willow chips biomass is used as feedstock in a biorefinery to produce E85 and in a heating plant to produce heat instead of the use of fossil sources. The shortage of oil, the global increases of CO_2 eq emissions, the increasing interest for biodegradable products, together with rural and environmental benefits associated with the willow cultivation (efficient land use, low economic investments, high biomass production potential, …) have promoted the interest on this energy crop.

Concerning the ethanol yield, a value of 0.223 kg/kg of green feedstock was obtained (see Table 3) which is in the same range as the ones obtained in other related studies where short rotation coppices were used as raw materials such as eucalyptus, black locust, and poplar (González-García et al. 2012b). In these studies, the ethanol yield ranged from 0.165 to 0.246 kg/kg green feedstock using the same methodology, hydrolysis process, and microorganisms. However, all these results of ethanol yield are consistent with other studies where different lignocellulosic feedstocks, microorganisms, hydrolysis, and fermentation conditions have been proposed Ewanick et al. 2007; Kumar et al. 2009; Luo et al. 2009a, b). Ewanick et al. (2007) proposed the use of lodgepole pine as feedstock with a yield of 0.244 kg/kg of green feedstock, which accounted for 77 % of the theoretical yield.

If the same production ratio as Ewanick et al. (2007) is considered here, 0.172 kg of ethanol per kilogram of green feedstock would be obtained. In addition, there should be a higher electricity surplus, since it is derived from solids from distillation, syrup, and biogas. Thus, the LCA characterization results per kilometer for E85 production and use should be slightly reduced in almost all the categories, except on terms of GWP, with reductions of around 1–2 %. Concerning the GWP, an increase of 28 % of the CO_2 equivalent emissions in

comparison with the base ethanol yield (0.09 kg CO_2eq/km versus 0.19 kg CO_2 eq/km) would be obtained. Concerning the comparison with the production and use of CG (alternative A2), the reduction in terms of GHG emissions should be around 54 %. Slight differences should be indentified for the remaining impact categories.

5 Conclusions

This study highlights the opportunities and challenges for willow chip biomass for two different energy uses: The production of lignocellulosic ethanol and its use blended with gasoline in a FFV, on the one hand, and its combustion in an industrial boiler for heat production, on the other. Both energy systems were analyzed in detail from an environmental point of view using the LCA perspective in order to identify the most problematic environmental hot spots and to propose improvement alternatives. In addition, both bioenergy systems were compared with conventional systems, these are the case of the production and use of gasoline and the production of heat from natural gas.

According to the calculations, Swedish willow biomass production is energetically efficient and the destination of this biomass for energy purposes (independently of the type of energy) presents environmental benefits in terms of GHG avoided emissions and fossil fuels depletion. However, potential improvement actions can be developed regarding the fertilizing process (e.g., reduction of the dose of N-based fertilizer) in order to reduce the contributions from willow chip production subsystem to the environmental profiles. The use of diesel in agricultural activities also considerably affected the environmental results (such as in OLD and toxicity categories). Therefore, the introduction of biodiesel in agricultural activities could remarkably improve the profile. Moreover, special attention should be paid on the ethanol production-related activities specifically, in terms of acetic acid emissions which showed high contributions to PO.

Finally, the capacity of CO_2 fixation by the biomass must be included in the analysis due to the positive environmental benefits in terms of GWP.

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